Chapter 6

Review of the New Combustion Technologies in Modern Gas Turbines

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Additional information is available at the end of the chapter

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1. Introduction

The combustion chamber is the most critical part of a gas turbine. The chamber had to be designed so that the combustion process to sustain itself in a continuous manner and the temperature of the products is sufficiently below the maximum working temperature in the turbine. In the conventional industrial gas turbine combustion systems, the combustion chamber can be divided into two areas: the primary zone and the secondary zone. The primary zone is where the majority of the fuel combustion takes place. The fuel must be mixed with the correct amount of air so that a stoichiometric mixture is present. In the secondary zone, unburned air is mixed with the combustion products to cool the mixture before it enters the turbine. In some design, there is an intermediate zone where help secondary zone to eliminate the dissociation products and burn-out soot.

The majority of the combustors are developed base on diffusion flames as they are very stable and fuel flexibility option. In a diffusion flame, there will be always stoichiometric regions regardless of overall stoichiometry. The main disadvantage of diffusion-type combustor is the emission as high temperature of the primary zone produced larger than 70 ppm NOx in burning natural gas and more than 100 ppm for liquid fuel [1]. Several techniques have been tried in order to reduce the amount of NOx produced in conventional combustors. In general, it is difficult to reduce NOx emissions while maintaining a high combustion efficiency as there is a tradeoff between NOx production and CO/UHC production.

In some recent installations, the premixed type of combustion has been selected to reduce NOx emissions bellow 10 ppm. Apart from the flame type change, there are some method such as "wet diffusion combustion", FGR[1] and SCR[2]. In an example of wet combustion, a nuzzle through which steam is injected is provided in the vicinity of the fuel injector. The level of NOx emission is controlled by the amount of steam. However, there is a limit on the increasing the steam flow rate as cause corresponding considerable CO emission. Furthermore, preparing pure steam in the required injection condition increases operational costs. Nowadays, wet combustion rarely applies due to water consumption and the penalty of reduced efficiency. Post Combustion treatments such as SCR are those which convert NOx compounds to nitrogen or absorb them from flue gas. These methods are relatively inexpensive to install but does not achieve NOx removal levels better than modern gas turbine combustor.

In this chapter, a short introduction of combustion process and then a description of some new pioneer combustor have been presented. As gas turbine manufacturers are looking for continuous operation or stable combustion, satisfactory emission level, minimum pressure loss and durability or life. Hence, the advanced combustor might include all of these criteria, so some of them are selected to discuss in details.

2. The combustion process

2.1. Type of combustion chamber

The diffusion and premixed flame are two main type of combustion, which are using in gas turbines. Apart from type of flame, there are two kind of combustor design, annular and tubular. The annular type mostly recommended in the propulsion of aircraft when small cross section and low weight are important parameters. Can or tubular combustors are cheaper and several of them can be adjusted for an industrial engine identically. Although there are different types of combustors, but generally, all combustion chambers have a diffuser, a casing, a liner, a fuel injector and a cooling arrangement. An entire common layout is visualized in figure 1.

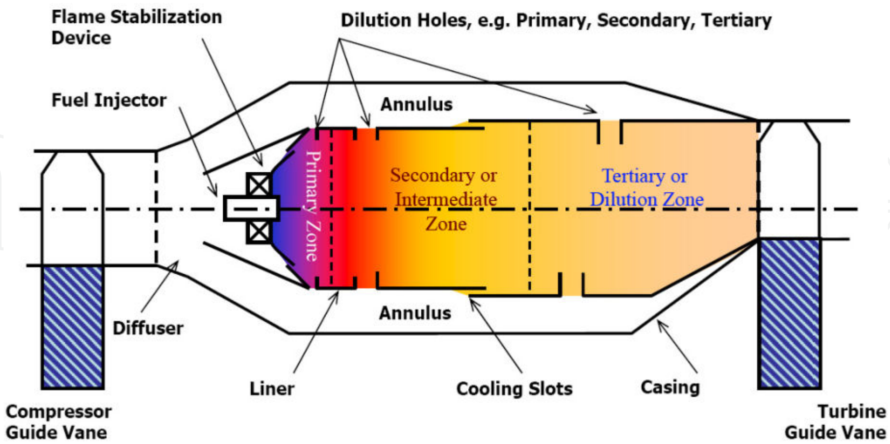

Figure 1. The layout of the combustion chamber.

1 Flue Gas Recirculation

2 Selective Catalytic Reduction

2.2. Flame stabilization

After the fuel has been injected into the air flow, the flow will enter the flame region. It does this with quite a high velocity, so to make sure the flame isn't blown away; suitable flame stabilization techniques must be applied. First, the high velocity of flow will be responsible for a pressure drop[3]. Secondly, the flame in the combustion chamber cannot survive if the air has a high velocity. So combustion chambers benefit from diffusers to slow down the air flow. There are two normal kinds of flame stabilizers: bluff-body flame holders and swirlers.

The shape of the bluff–body flame holder affects the flow stability characteristics through the influence on the size and shape of the wake region. Since the flame stabilization depends on size of the zone of recirculation behind the bluff–body, different geometries such as triangular, rectangular, circular and more complex shapes are being use. One of the basic problem of bluff-body flame holders is a considerable effect on pressure loss. Figure 2 shows a high speed image of three flame holders in atmospheric condition.

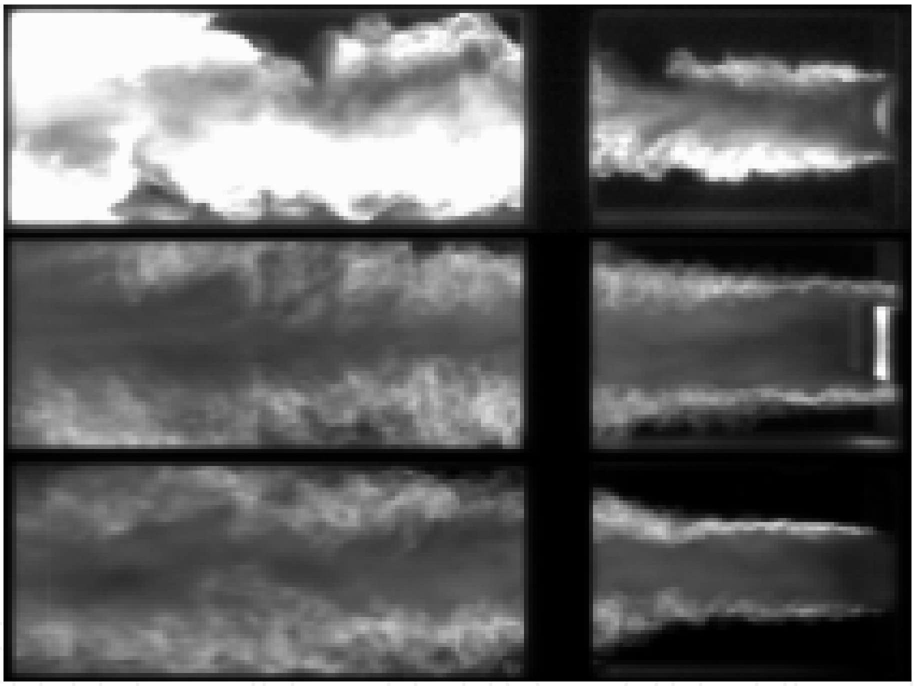

Figure 2. High speed images of the circular cylinder (top), square cylinder (middle) and V gutter (bottom) at Re = 30,000 and stoichiometric mixture [2].

Flow reversal can be applied in the primary zone. The best way to reverse the flow is to swirl it through using swirlers. The two most important types of swirlers are axial and radial. The advantage of flow reversal is that the flow speed varies a lot. So there will be a point at which the airflow velocity matches the flame speed where a flame could be stabilized. The degree of swirl in the flow is quantified by the dimensionless parameter, *Sn* known as the swirl number which is defined as:

3 This pressure drop is named the cold loss.

$$Sn = \frac{G_\theta}{G_x r} \tag{1}$$

Where:

$$G_\theta = \int_0^\infty (\rho u w + \overline{\rho u' w'}) r^2 dr$$

$$G_x = \int_0^\infty (\rho u^2 + \overline{\rho u'^2} + (p - p_\infty)) r dr$$

As this equation requires velocity and pressure profile of fluid, researchers proposed various expressions for calculating the swirl number. Indeed, the swirl number is a non-dimensional number representing the ratio of axial flux of angular momentum to the axial flux of axial momentum times the equivalent nozzle radius [3]. Tangential entry, guided vanes and direct rotation are three principal methods for generating swirl flow.

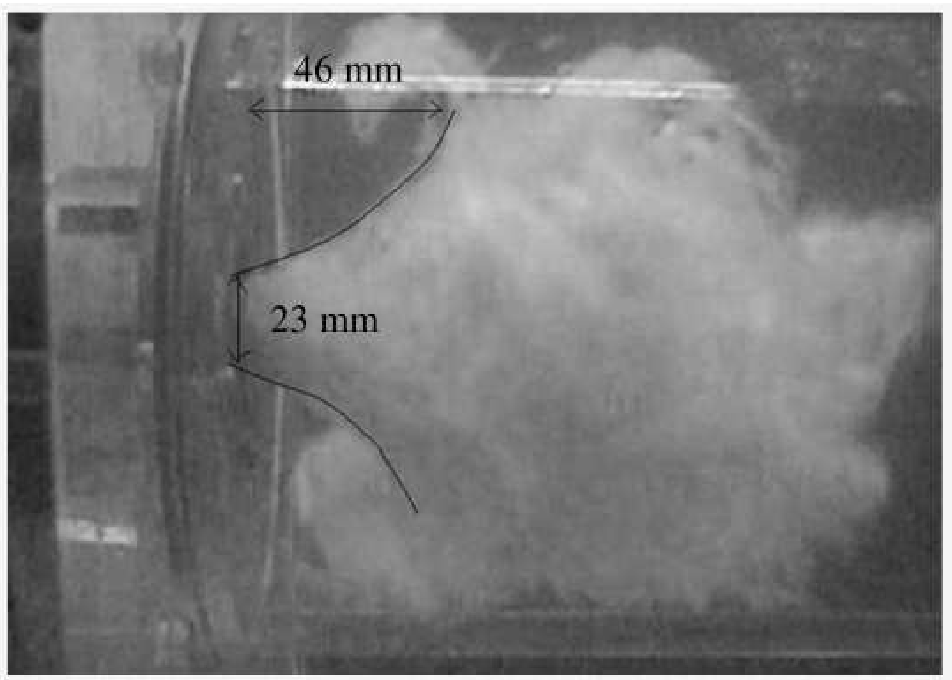

Figure 3. Photo of 60° flat guided vane swirler [4].

2.3. Type of flame

Most of the literatures divide combustible mixture into three categories as premixed, non-premixed and partially premixed combustion. If fuel and oxidizer are mixed prior ignition, then premixed flame will propagate into the unburned reactants. If fuel and air mix at the same time and same place as they react, the diffusion or non-premixed combustion will appear. Partially premixed combustion systems are premixed flames with non-uniform fuel-oxidizer mixtures.

Gas turbines' manufacturers traditionally tend to use diffusion flame where fuel mixes with air by turbulent diffusion and the flame front stabilized in the locus of the stoichiometric mixture. The temperature of reactant is as high as 2000 °C, so the acceptable temperature at the combustor walls and turbine blades would be provide by diluted air. Although the non-premixed mixture in gas turbine combustors shows more stability in operation than premixed mixtures, but their shortcoming is high level of nitrogen oxide emission. Two most common ways of emission reduction are water injection and catalytic converter. However, the former technique is not capable of reducing NOx to the expected level at many sites, while SCR adds complexity and expense to any project.

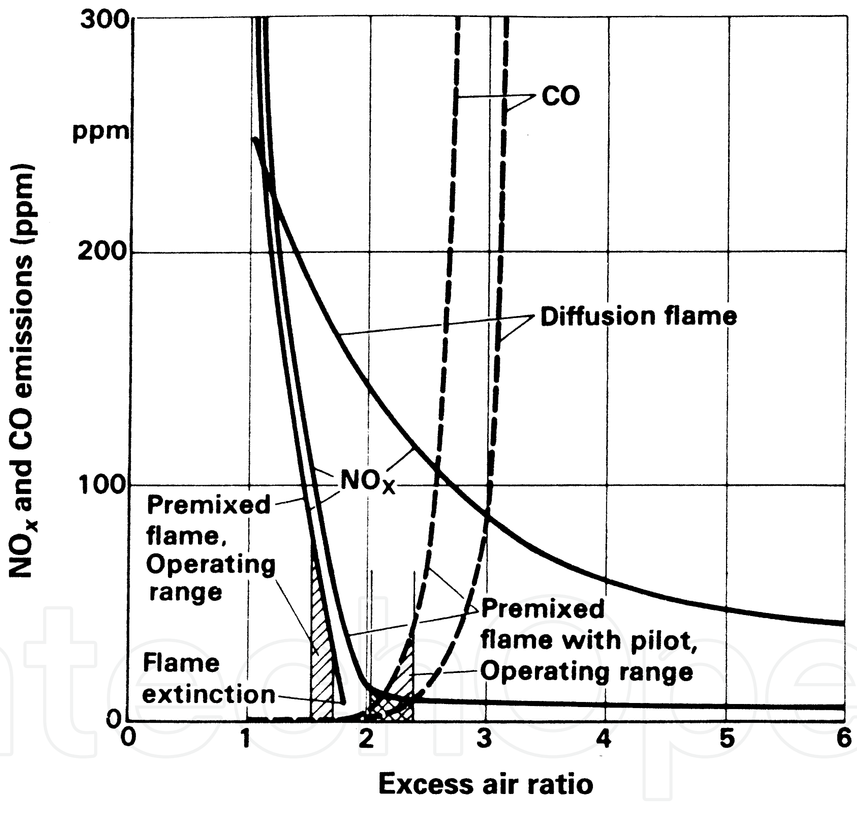

Figure 4. Operating range of premixed flames [5].

The idea of Dry Low NOx (DLN) systems proposed base on lean premixed combustion to reduce flame temperature by a non-stoichiometric mixture. Premixed systems can be operated at a much lower equivalence ratio such that the flame temperature and thermal NOx production throughout the system are decreased comparing with a diffusion system. The disadvantage of premixed systems is flame stability, especially at low equivalence ratios. Also, there is a tendency for the flame to flashback. Indeed, the current challenge of GT's developers is proposing a fuel flexible combustor for a stable combustion in all engine loads. The narrow range of fuel/air mixtures between the production of excessive NOx and excessive CO is illustrated in figure 4. NOx reduces by lowering flame temperature in a leaner mixture but CO, and unburned hydrocarbons (UHC) would increase contradictorily.

By increasing combustion residence time (volume) and preventing local quenching, CO and UHC will dissociate to CO2 and the other products. CO burns away more slowly than the other radicals, so to obtain very low level emission such as 10 ppm; it requires over 4 ms. As shown in figure 5, below 1100 °C the CO reaction becomes too slow to effectively remove the CO in an improved combustion chamber. The residence time usually does not change much on part-load because the normalized flow approximately remains constant with a variable loading.

$$NF = \frac{\dot{m}\sqrt{T}}{P} \tag{2}$$

Where $\dot{m}$ is the mass flow, T is combustion bulk temperature and P is combustor pressure. This will set a lower limit for the length of the primary zone in a DLN combustion system.

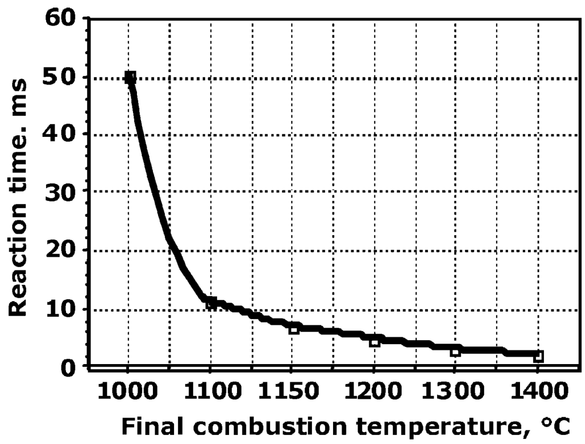

Figure 5. Calculated reaction time to achieve a CO concentration of 10 ppm in a commercial gas turbine exhaust [6].

2.4. Fuel

One of the features of heavy-duty gas turbines is a wide fuel capability. They can operate with vast series of commercial and process by-product fuels such as natural gas, petroleum distillates, gasified coal or biomass, gas condensates, alcohols, ash-forming fuels. In a review article, Molière offered essential aspects of fuel/machine interactions in thermodynamic performance, combustion and gaseous emission [7]. To sequester and store the CO2 of fossil fuel, some new research projects aim to assess the combustion performances of alternative fuels for clean and efficient energy production by gas turbines. Another objective is to extend the capability of dry low emission gas turbine technologies to low heat value fuels produced by gasification of biomass and H2 enriched fuels [8-10]. Significant quantity of hydrogen in fuel has the benefit of high calorific value, but the disadvantage of high flame speed and very fast chemical times. To classify gas turbine's fuels, a common way is to split them between gas and liquid fuels, and within the gaseous fuels, to split by their calorific value as shown in table 1.

	Typical composition	Lower Heating Value kJ/Nm³	Typical specific fuels
Ultra/Low LHV gaseous fuels	$H_2 < 10\%$ $CH_4 < 10\%$ $N_2+CO > 40\%$	< 11,200 (< 300)	Blast furnace gas (BFG), Air blown IGCC, Biomass gasification
High hydrogen gaseous fuels	$H_2 > 50\%$ $C_xH_y = 0\text{-}40\%$	5,500-11,200 (150-300)	Refinery gas, Petrochemical gas, Hydrogen power
Medium LHV gaseous fuels	$CH_4 < 60\%$ $N_2+CO_2 = 30\text{-}50\%$ $H_2 = 10\text{-}50\%$	11,200-30,000	Weak natural gas, Landfill gas, Coke oven gas, Corex gas
Natural gas	$CH_4 = 90\%$ $C_xH_y = 5\%$ Inert = 5%	30,000-45,000	Natural gas Liquefied natural gas
High LHV gaseous fuels	CH_4 and higher hydrocarbons $C_xH_y > 10\%$	45,000-190,000	Liquid petroleum gas (butane, propane) Refinery off-gas
Liquid fuels	C_xH_y, with $x > 6$	32,000-45,000	Diesel oil, Naphtha Crude oils, Residual oils, Bio-liquids

Table 1. Classification of fuels [11].

3. New combustion systems for gas turbines

Next-generation gas turbines will operate at higher pressure ratios and hotter turbine inlet temperatures conditions that will tend to increase nitrogen oxide emissions. To conform to future air quality requirements, lower-emitting combustion technology will be required. In this section, a number of new combustion systems have been introduced where some of them could be found in the market, and the others are under development.

3.1. Trapped vortex combustion (TVC)

The trapped vortex combustor (TVC) may be considered as a promising technology for both pollutant emissions and pressure drop reduction. TVC is based on mixing hot combustion products and reactants at a high rate by a cavity stabilization concept. The trapped vortex combustion concept has been under investigation since the early 1990's. The earlier studies of TVC have been concentrated on liquid fuel applications for aircraft combustors [12].

The trapped vortex technology offers several advantages as gas turbines burner:

- It is possible to burn a variety of fuels with medium and low calorific value.
- It is possible to operate at high excess air premixed regime, given the ability to support high-speed injections, which avoids flashback.
- NOx emissions reach extremely low levels without dilution or post-combustion treatments.
- Produces the extension of the flammability limits and improves flame stability.

Flame stability is achieved through the use of recirculation zones to provide a continuous ignition source which facilitates the mixing of hot combustion products with the incoming fuel and air mixture [13]. Turbulence occurring in a TVC combustion chamber is "trapped" within a cavity where reactants are injected and efficiently mixed. Since part of the combustion occurs within the recirculation zone, a "typically" flameless regime can be achieved, while a trapped turbulent vortex may provide significant pressure drop reduction [14]. Besides this, TVC is having the capability of operating as a staged combustor if the fuel is injected into both the cavities and the main airflow. Generally, staged combustion systems are having the potential of achieving about 10 to 40% reduction in NOx emissions [15]. It can also be operated as a rich-burn, quick-quench lean-burn (RQL) combustor when all of the fuel is injected into the cavities [16].

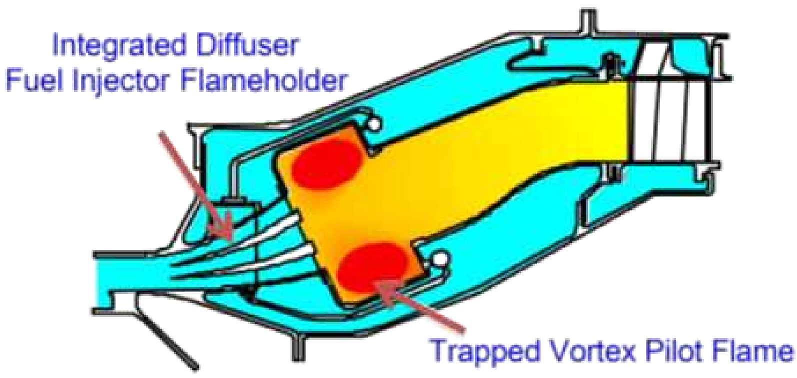

Figure 6. Trapped vortex combustor schematic.

An experiment in NASA with water injected TVC demonstrated a reduction in NOx by a factor three in a natural gas fueled and up to two in a liquid JP-8 fueled over a range in water/fuel and fuel/air ratios [17]. Replacement of natural gas fuel with syngas and hydrogen fuels has been studied numerically by Ghenai et al. [18]. The effects of secondary air jet momentum on cavity flow structure of TVC have been studied recently by Kumar and Mishra [19]. Although the actual stabilization mechanism facilitated by the TVC is relatively simple, a number of experiments and numerical simulations have been performed to enhance the stability of reacting flow inside trapped vortex. Xing et al. experimentally investigated lean blow-out of several combustors and the performance of slight temperature-raise in a single trapped vortex [20, 21]. In an experimental laboratory research, Bucher et al. proposed a new design for lean-premixed trapped vortex combustor [22].

3.2. Rich burn, quick- mix, lean burn (RQL)

Lean direct injection (LDI) and rich-burn/quick-quench/lean-burn (RQL) are two of the prominent low-emissions concepts for gas turbines. LDI operates the primary combustion region lean, hence, adequate flame stabilization has to be ensured; RQL is rich in the primary zone with a transition to lean combustion by rapid mixing with secondary air downstream. Hence, both concepts avoid stoichiometric combustion as much as possible, but flame stabilization and combustion in the main heat release region are entirely different. Relative to aviation engines, the need for reliability and safety has led to a focus on LDI of liquid fuels [23]. However, RQL combustor technology is of growing interest for stationary gas turbines due to the attributes of more effectively processing of fuels with complex composition. The concept of RQL was proposed in 1980 as a significant effort for reducing NOx emission [24].

It is known that the primary zone of a gas turbine combustor operates most effectively with rich mixture ratios so, a “rich-burn” condition in the primary zone enhances the stability of the combustion reaction by producing and sustaining a high concentration of energetic hydrogen and hydrocarbon radical species. Secondly, rich burn conditions minimize the production of nitrogen oxides due to the relative low temperatures and low population of oxygen containing intermediate species. Critical factors of a RQL that need to be considered are careful tailoring of rich and lean equivalence ratios and very fast cooling rates. So the combustion regime shifts rapidly from rich to lean without going through the high NOx route as shown in figure 7. The drawback of this technology is increased hardware and complexity of the system.

The mixing of the injected air takes the reaction to the lean-burn zone and rapidly reduces their temperature as well. On the other hand, the temperature must be high enough to burn CO and UHC. Thus, the equivalence ratio for the lean-burn zone must be carefully selected to satisfy all emissions requirements. Typically the equivalence ratio of fuel-rich primary zone is 1.2 to 1.6 and lean-burn combustion occurs between 0.5 and 0.7 [25].

Turbulent jet in a cross-flow is an important characteristic of RQL; so many researches have been conducted to improve it. The mixing limitation in a design of RQL/TVC combustion system addressed by Straub et al. [26]. Coaxial swirling air discussed experimentally by Cozzi and Coghe [27]. Furthermore, an experimental study of the effects of elevated pressure and temperature on jet mixing and emissions in an RQL reported by Jermakian et al. [28]. Fuel flexible combustion with RQL system is an interest of turbine manufacturer. GE reported results of a RQL test stand in their integrated gasification combined cycle (IGCC) power plants program [29, 30]. The test of Siemens-Westinghouse Multi-Annular Swirl Burner (MASB) was successfully performed at the University of

Tennessee Space Institute in Tullahoma [31]. Others, such as references [32-35] utilize CFD to investigate the performance of RQL combustor.

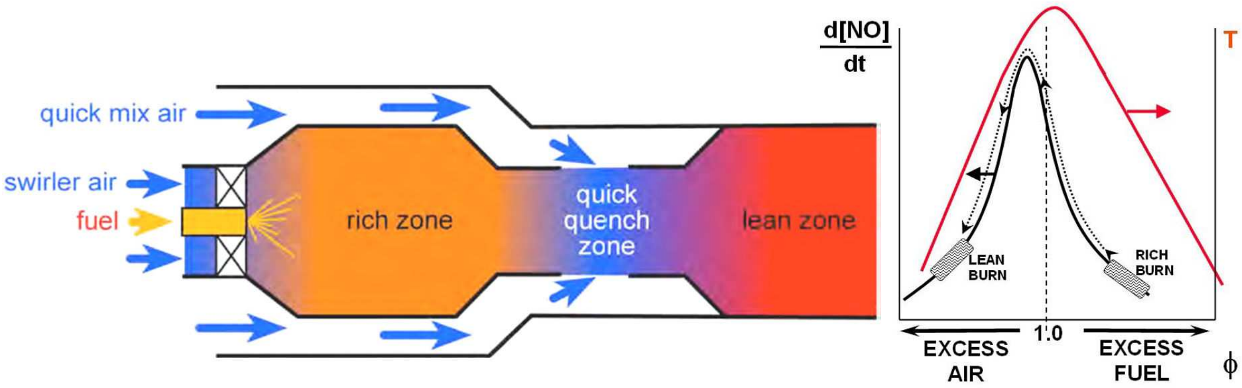

Figure 7. Rich-Burn, Quick-Mix, Lean-Burn combustor.

3.3. Staged air combustion

The COSTAIR[4] combustion concept uses continuously staged air and internal recirculation within the combustion chamber to obtain a stable combustion with low NOX and CO emissions. Research work on staged combustors started in the early 1970s under of the Energy Efficient Engine (E^3) Program in the USA [36] and now widely used in industrial engines burning gaseous fuels, in both axial and radial configurations. The aero-derived GE LM6000 and CFM56-5B as well as RR211 DLE industrial engine employ staged combustion of premixed gaseous fuel/air mixtures. Recently, a research project proposed a COSTAIR burner system optimized for low calorific gases within a micro gas turbine [37].

The principle of staged air combustion is illustrated in Figure 8. It consists of a coaxial tube; the combustion air flows through the inner tube and the fuel through the outer cylinder ring. The combustion air is continually distributed throughout the combustion chamber by an air distributor with numerous openings on its contour, and fuel enters by several jets arranged around the air distributor.

The COSTAIR burner has the advantages of operating in full diffusion mode or in partially premixed mode. The heat is released more uniformly throughout the combustion chamber also the recirculated gas absorb some of the heat of combustion. It capable to work stable at cold combustor walls as well as high air ratio. Experimental measurements show that this combustion system allows clean exhaust. For instance, in an experimental research project of European Commission [39], NOx emission values was in the range of 2-4 ppm at an air ratio of 2.5 over different loading. Furthermore, the corresponding CO emission was less than 7 ppm.

4 COntinuous STaged Air

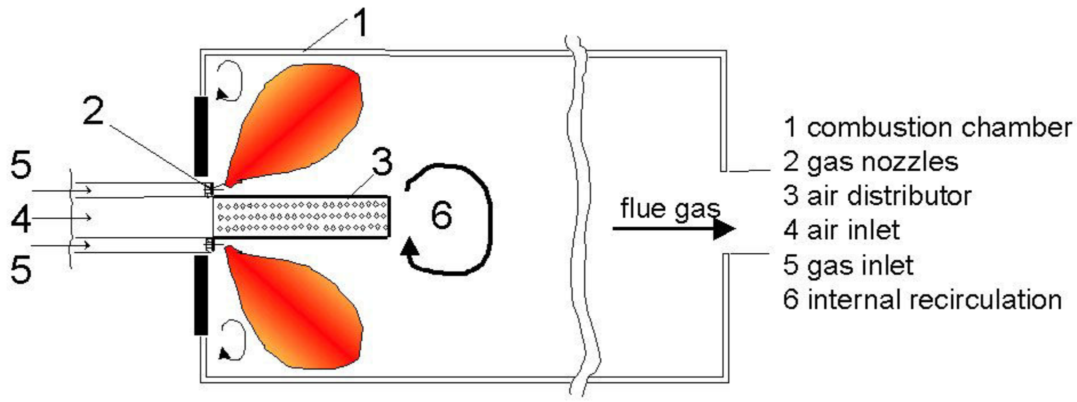

Figure 8. COSTAIR combustion concept [38].

Staged combustion can occur in either a radial or axial pattern, but in either case the goal is to design each stage to optimize particular performance aspects. The main advantages or major drawbacks of each type have been discussed by Lefebvre [25].

3.4. Mild combustion

Heat recirculating combustion was clearly described by Weinberg as a concept for improving the thermal efficiency [40]. In 1989, a surprising phenomenon was observed during experiments with a self-recuperative burner. At furnace temperatures of 1000°C and about 650°C air preheated temperature; no flame could be seen, but the fuel was completely burnt. Furthermore, the CO and NOx emissions from the furnace were considerably low [41]. Different combustion zones against rate of dilution and oxygen content is shown in figure 9. In flameless combustion, the oxidation of fuel occurs with a very limited oxygen supply at a very high temperature. Spontaneous ignition occurs and progresses with no visible or audible signs of the flames usually associated with burning. The chemical reaction zone is quite diffuse, and this leads to almost uniform heat release and a smooth temperature profile. All these factors could result in a much more efficient process as well as reducing emissions.

Flameless combustion is defined where the reactants exceed self-ignition temperature as well as entrain enough inert combustion products to reduce the final reaction temperature [42]. In the other word, the essence of this technology is that fuel is oxidized in an environment that contains a substantial amount of inert (flue) gases and some, typically not more than 3–5%, oxygen. Several different expressions are used to identify similar though such as HiTAC[5], HiCOT[6], MILD[7] combustion, FLOX[8] and CDC[9]. HiTAC refers to increase the air temperature by preheating systems such as regenerators. HiCOT commonly belongs to the

5 High Temperature Air Combustion

6 High-temperature Combustion Technology

7 Moderate or Intense Low-oxygen Dilution

8 FLameless OXidation

9 Colorless Distributed Combustion

wider sense, which exploits high-temperature reactants; therefore, it is not limited to air. A combustion process is named FLOX or MILD when the inlet temperature of the main reactant flow is higher than mixture autoignition temperature and the maximum allowable temperature increase during combustion is lower than mixture autoignition temperature, due to dilution [42]. The common key feature to achieve reactions in CDC mode (non-premixed conditions) is the separation and controlled mixing of higher momentum air jet and the lower momentum fuel jet, large amount of gas recirculation and higher turbulent mixing rates to achieve spontaneous ignition of the fuel to provide distributed combustion reactions [43]. Figure 10 schematically shows a comparison between conventional burner and flameless combustion.

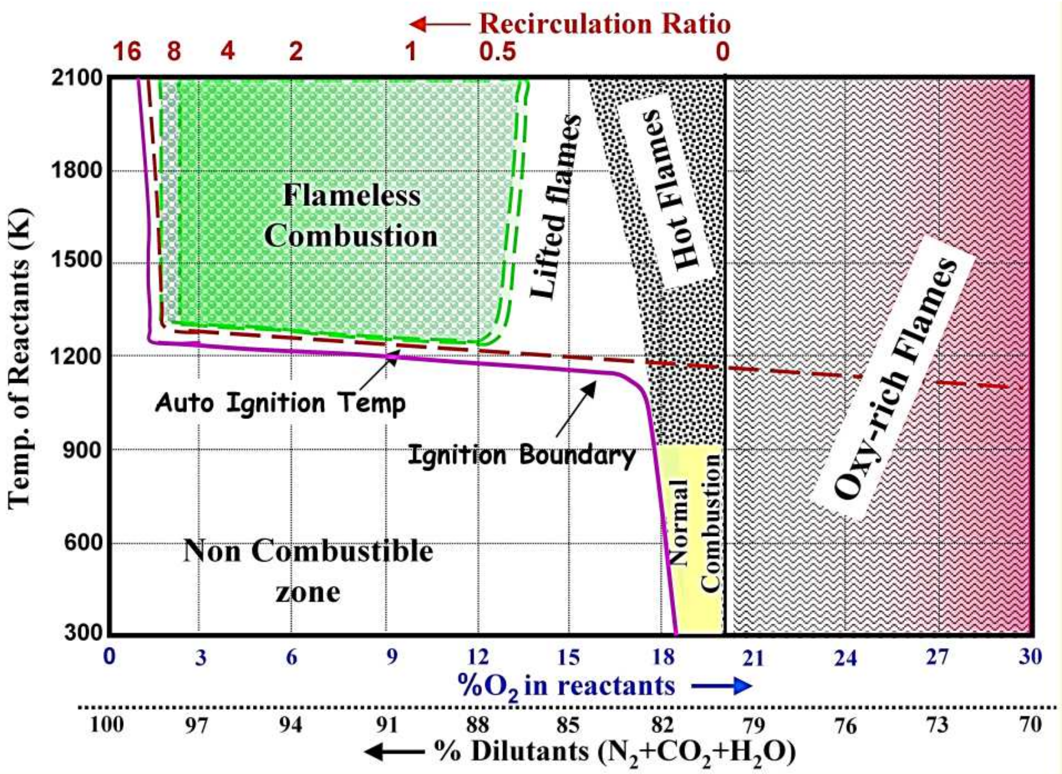

Figure 9. Different combustion regimes [64].

To recap, the main characteristics of flameless oxidation combustion are:

- Recirculation of combustion products at high temperature (normally > 1000 °C),
- Reduced oxygen concentration at the reactance,
- Low Damköhler number (Da[10]),
- Low stable adiabatic flame temperature,
- Reduce temperature peaks,

10 A dimensionless number, equal to the ratio of the turbulence time scale to the time it takes chemical reaction.

- Highly transparent flame,
- Low acoustic oscillation and
- Low NOx and CO emissions.

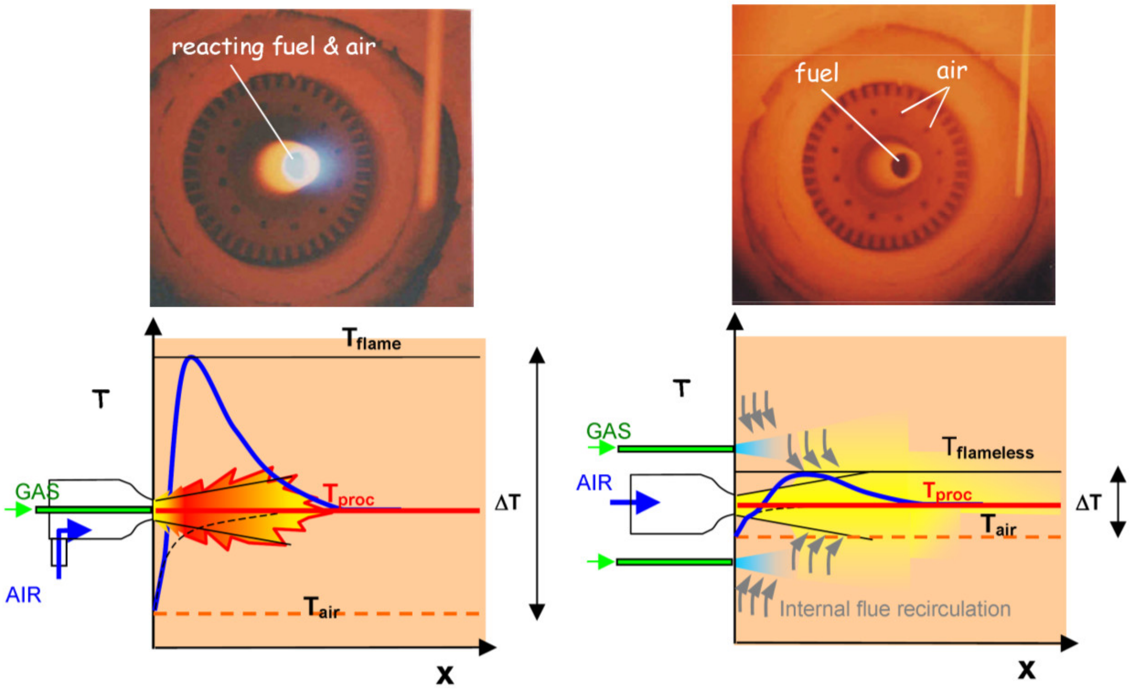

Figure 10. Flame (left) and flameless (right) firing.

In spite of a number of activities for industrial furnaces, the application of flameless combustion in the gas-turbine combustion system is in the preliminary phase [44]. The results from techno-economic analysis of Wang et al. showed that the COSTAIR and FLOX cases had technical and economic advantages over SCR [45]. Luckerath, R., et al., investigated flameless combustion in forward flow configuration in elevated pressure up to 20atm for application to gas turbine combustors [44, 46]. In a novel design of Levy et al. that named FLOXCOM, flameless concept has been proposed for gas turbines by establishing large recirculation zone in the combustion chamber [47, 48]. Lammel et al. developed a FLOX combustion at high power density and achieved low NOx and CO levels [49]. The concept of colorless distributed combustion has been demonstrated by Gupta et al. for gas turbine application in a number of publications [43, 50-55].

3.5. Surface stabilized combustion

One specification of gas turbine combustor is higher thermal intensity range (at least 5 MW/m^3-atm) than industrial furnaces which operate at thermal intensity of less than 1 MW/m^3-atm. Therefore, designs of gas turbine's combustors are based on turbulent flow concept, except a technology named NanoSTAR from Alzeta Corporation. Alzeta reported the proof-of-concept of high thermal intensity laminar surface stabilized flame by using a porous metal-fiber mat since 2001 [56-58]. Lean premixed combustion technology is limited by the apparition of combustion instabilities, which induce high pressure fluctuations, which can produce turbine damage, flame extinction, and CO emissions [59]. However, full scale test of NanoSTAR demonstrated low emissions performance, robust ignition and extended turndown ratio [60]. In particular, the following characteristics form the key specifications of NanoSTAR for distributed power generation gas turbine combustors [61]:

- The combustor fuel is limited to natural gas.
- Total combustor pressure drop limited to 2-4% of the system pressure.
- Operation at combustion air preheat temperatures up to 1150°F.
- Volumetric firing rates approaching 2 MMBtu/hr/atm/ft^3.
- Turbine Rotor Inlet Temperatures (TRIT) over 2200°F (valid for the Mercury 50, although Allison has operated combustors at 2600°F).
- Operation with axial combustors or external can combustors.
- Expected component lifetimes of 30,000 hours for industrial turbines.

A single prototype burner Porous burner which sized to fit inside an annular combustion liner (about 2.5 inches in diameter by 7 inches in length) is shown in figure 11 with its arrangement in a typical combustor.

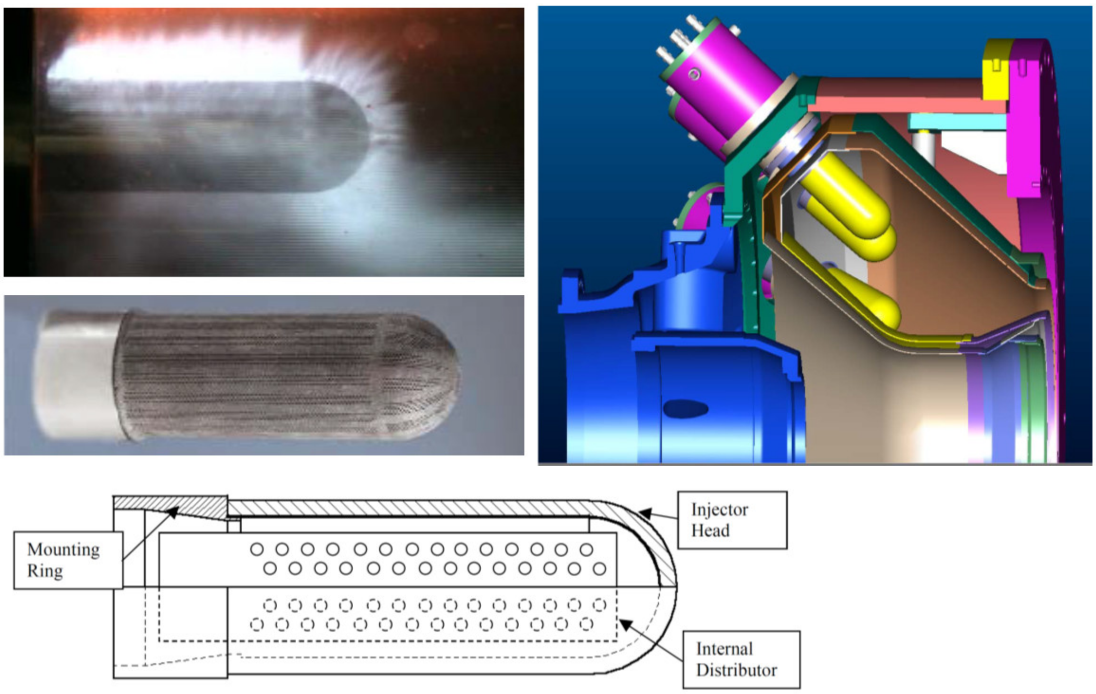

Figure 11. NanoSTAR burner and its arrangement in a canted combustion system [62].

The operation of this type of surface stabilized combustion is characterized by the schematic in Figure 12(left), which shows premixed fuel and air passing through the metal fiber mat in two distinct zones. Premixed fuel comes through the low conductivity porous and burns in narrow zones, A, as it leaves the surface. Under lean conditions this will manifest as very short laminar flamelets, but under rich conditions the surface combustion will become a diffusion dominated reaction stabilized just over a millimeter above the metal matrix, which proceeds without visible flame and heats the outer surface of the mat to incandescence. Secondly, adjacent to these radiant zones, the porous plate is perforated to allow a high flow of the premixed fuel and air. This flow forms a high intensity flame, B, stabilized by the radiant zones so, it is possible to achieve very high fluxes of energy, up to 2MMBtu/hr/ft^2 [63]. A picture of an atmospheric burner in operation clearly shows the technology in action (right of figure 12).

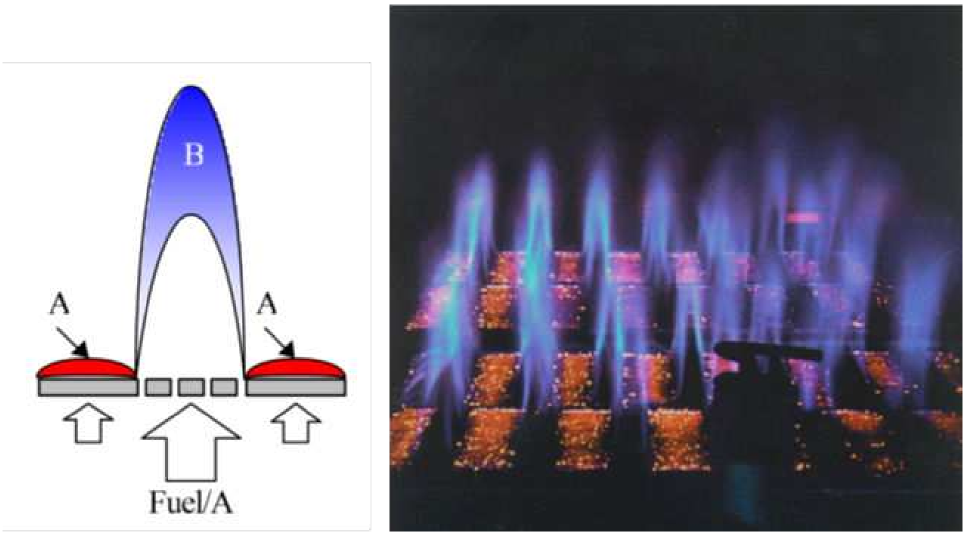

Figure 12. Surface stabilized burner pad firing at atmospheric conditions.

The specific perforation arrangement and pattern control the size and shape of the laminar flamelets. The perforated zones operate at flow velocities of up to 10 times the laminar flame speed producing a factor of ten stretch of the flame surface and resulting in a large laminar flamelets. The alternating arrangement of laminar blue flames and surface combustion, allows high firing rates to be achieved before flame liftoff occurs, with the surface combustion stabilizing the long laminar flames by providing a pool of hot combustion radicals at the flame edges.

4. Conclusion

A review of technologies for reducing NOx emissions as well as increasing thermal efficiency and improving combustion stability has been reported here. Trade-offs when installing low NOx burners in gas turbines include the potential for decreased flame stability, reduced operating range and more strict fuel quality specifications. In the other word, although, the turbine inlet temperature is the major factor determining the overall efficiency of the gas turbine but higher inlet temperatures will result in larger NOx emissions. So the essential requirement of new combustor design is a trade-off between low NOx and improved efficiency.

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References

[1] Chambers A and Trottier S (2007) Technologies for Reducing Nox Emissions from Gas-Fired Stationary Combustion Sources. Alberta Research Council, Edmonton, Canada

[2] Kiel B, Garwick LK, Gord JR, Miller J, Lynch A, Hill R and Phillips S (2007) A Detailed Investigation of Bluff Body Stabilized Flames. 45th AIAA Aerospace Sciences Meeting and Exhibit.

[3] Gupta AK, Lilley DG and Syred N (1984) Swirl Flows, Abacus Press.

[4] Jaafar MNM, Jusoff K, Osman MS and Ishak MSA (2011) Combustor Aerodynamic Using Radial Swirler. International Journal of the Physical Sciences. 6: 3091 - 3098.

[5] Moore MJ (1997) Nox Emission Control in Gas Turbines for Combined Cycle Gas Turbine Plant. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy. 211: 43-52.

[6] Kajita S and Dalla Betta R (2003) Achieving Ultra Low Emissions in a Commercial 1.4 Mw Gas Turbine Utilizing Catalytic Combustion. Catalysis Today. 83: 279-288.

[7] Molière M (2000) Stationary Gas Turbines and Primary Energies: A Review of Fuel Influence on Energy and Combustion Performances. International Journal of Thermal Sciences. 39: 141-172.

[8] Gupta KK, Rehman A and Sarviya RM (2010) Bio-Fuels for the Gas Turbine: A Review. Renewable and Sustainable Energy Reviews. 14: 2946-2955.

[9] Gökalp I and Lebas E (2004) Alternative Fuels for Industrial Gas Turbines (Aftur). Applied Thermal Engineering. 24: 1655-1663.

[10] Juste GL (2006) Hydrogen Injection as Additional Fuel in Gas Turbine Combustor. Evaluation of Effects. International Journal of Hydrogen Energy. 31: 2112-2121.

[11] Jones R, Goldmeer J and Monetti B (2011) Addressing Gas Turbine Fuel Flexibility. GE Energy

[12] Haynes J, Janssen J, Russell C and Huffman M (2006) Advanced Combustion Systems for Next Generation Gas Turbines. United States. Dept. of Energy, Washington, D.C.; Oak Ridge, Tenn.

[13] Sturgess GJ and Hsu KY (1998) Combustion Characteristics of a Trapped Vortex Combustor. Applied vehicle technology panel symposium.

[14] Bruno C and Losurdo M (2007) The Trapped Vortex Combustor: An Advanced Combustion Technology for Aerospace and Gas Turbine Applications. In: Syred N and Khalatov A, Syred N and Khalatov A, editors. Advanced Combustion and Aerothermal Technologies. Springer Netherlands, pp 365-384.

[15] Mishra DP (2008) Fundamentals of Combustion, Prentice-Hall Of India Pvt. Limited.

[16] Acharya S, Mancilla PC and Chakka P (2001) Performance of a Trapped Vortex Spray Combustor. ASME International Gas Turbine Conference. ASME.

[17] Hendricks RC, Shouse DT and Roquemore WM (2005) Water Injected Turbomachinery. NASA, Glenn Research Center

[18] Ghenai C, Zbeeb K and Janajreh I (2012) Combustion of Alternative Fuels in Vortex Trapped Combustor. Energy Conversion and Management. In press

[19] Ezhil Kumar PK and Mishra DP (2011) Numerical Simulation of Cavity Flow Structure in an Axisymmetric Trapped Vortex Combustor. Aerospace Science and Technology. In Press

[20] Xing F, Wang P, Zhang S, Zou J, Zheng Y, Zhang R and Fan W (2012) Experiment and Simulation Study on Lean Blow-out of Trapped Vortex Combustor with Various Aspect Ratios. Aerospace Science and Technology. 18: 48-55.

[21] Xing F, Zhang S, Wang P and Fan W (2010) Experimental Investigation of a Single Trapped-Vortex Combustor with a Slight Temperature Raise. Aerospace Science and Technology. 14: 520-525.

[22] Bucher J, Edmonds RG, Steele RC, Kendrick DW, Chenevert BC and Malte PC (2003) The Development of a Lean-Premixed Trapped Vortex Combustor. ASME Turbo Expo 2003 Power for Land, Sea, and Air.

[23] Dunn-Rankin D (2008) Lean Combustion: Technology and Control, Academic Press, USA.

[24] Mosier SA and Pierce RM (1980) Advanced Combustion Systems for Stationary Gas Turbine Engines. Volume I. Review and Preliminary Evaluation. Final Report December 1975-September 1976. pp Medium: X; Size: Pages: 49.

[25] Lefebvre AH and Ballal DR (2010) Gas Turbine Combustion: Alternative Fuels and Emissions, Taylor & Francis.

[26] Straub DL, Casleton KH, Lewis RE, Sidwell TG, Maloney DJ and Richards GA (2005) Assessment of Rich-Burn, Quick-Mix, Lean-Burn Trapped Vortex Combustor for Stationary Gas Turbines. Journal of engineering for gas turbines and power. 127: 36-41.

[27] Cozzi F and Coghe A (2012) Effect of Air Staging on a Coaxial Swirled Natural Gas Flame. Experimental Thermal and Fluid Science. In press

[28] Jermakian V, McDonell VG and Samuelsen GS (2012) Experimental Study of the Effects of Elevated Pressure and Temperature on Jet Mixing and Emissions in an Rql Combustor for Stable, Efficient and Low Emissions Gas Turbine Applications. Advanced Power and Energy Program, University of California, Irvine

[29] Feitelberg AS, Jackson MR, Lacey MA, Manning KS and Ritter AM (1996) Design and Performance of a Low Btu Fuel Rich-Quench-Lean Gas Turbine Combustor. Advanced coal-fired power systems review meeting. USA DOE, Morgantown Energy Technology Center.

[30] Feitelberg AS and Lacey MA (1998) The Ge Rich-Quench-Lean Gas Turbine Combustor. Journal of Engineering for Gas Turbines and Power, Transactions of the ASME. 120: 502-508.

[31] Brushwood J (1999) Syngas Combustor for Fluidized Bed Applications 15th Annual Fluidized Bed Conference.

[32] Howe GW, Li Z, Shih TI-P and Nguyen HL (1991) Simulation of Mixing in the Quick Quench Region of a Richburn-Quick Quench Mix-Lean Burn Combustor. 29th Aerospace Sci Meeting. AIAA.

[33] Cline MC, Micklow GJ, Yang SL and Nguyen HL (1992) Numerical Analysis of the Flow Fields in a Rql Gas Turbine Combustor.

[34] Talpallikar MV, Smith CE, Lai MC and Holdeman JD (1992) Cfd Analysis of Jet Mixing in Low Nox Flametube Combustors. Journal of Engineering for Gas Turbines and Power. 114: 416-424.

[35] Blomeyer M, Krautkremer B, Hennecke DK and Doerr T (1999) Mixing Zone Optimization of a Rich-Burn/Quick-Mix/Lean-Burn Combustor. Journal of Propulsion and Power 15: 288-303.

[36] Wulff A and Hourmouziadis J (1997) Technology Review of Aeroengine Pollutant Emissions. Aerospace Science and Technology. 1: 557-572.

[37] Leicher J, Giese A, Görner K, Scherer V and Schulzke T (2011) Developing a Burner System for Low Calorific Gases in Micro Gas Turbines: An Application for Small Scale Decentralized Heat and Power Generation International Gas Union Research Conference.

[38] Al-Halbouni A, Flamme M, Giese A, Scherer V, Michalski B and Wünning JG (2004) New Burner Systems with High Fuel Flexibility for Gas Turbines. 2nd International Conference on Industrial Gas Turbine Technologies.

[39] Flamme M (2004) New Combustion Systems for Gas Turbines (Ngt). Applied Thermal Engineering. 24: 1551-1559.

[40] WEINBERG F (1996) Heat-Recirculating Burners : Principles and Some Recent Developments. Combustion Science and Technology. 121: 3-22.

[41] Wünning J (2005) Flameless Oxidation. 6th HiTACG Symposium.

[42] Cavaliere A and de Joannon M (2004) Mild Combustion. Progress in Energy and Combustion Science. 30: 329-366.

[43] Arghode VK, Gupta AK and Bryden KM (2012) High Intensity Colorless Distributed Combustion for Ultra Low Emissions and Enhanced Performance. Applied Energy. 92: 822-830.

[44] Li P, Mi J, Dally B, Wang F, Wang L, Liu Z, Chen S and Zheng C (2011) Progress and Recent Trend in Mild Combustion. SCIENCE CHINA Technological Sciences. 54: 255-269.

[45] Wang YD, Huang Y, McIlveen-Wright D, McMullan J, Hewitt N, Eames P and Rezvani S (2006) A Techno-Economic Analysis of the Application of Continuous Staged-Combustion and Flameless Oxidation to the Combustor Design in Gas Turbines. Fuel Processing Technology. 87: 727-736.

[46] Luckerath R, Meier W and Aigner M (2008) Flox Combustion at High Pressure with Different Fuel Compositions. Journal of Engineering for Gas Turbines and Power. 130: 011505.

[47] Costa M, Melo M, Sousa J and Levy Y (2009) Experimental Investigation of a Novel Combustor Model for Gas Turbines. Journal of Propulsion and Power 25: 609-617.

[48] Levy Y, Sherbaum V and Arfi P (2004) Basic Thermodynamics of Floxcom, the Low-Nox Gas Turbines Adiabatic Combustor. Applied Thermal Engineering. 24: 1593-1605.

[49] Lammel O, Schutz H, Schmitz G, Luckerath R, Stohr M, Noll B, Aigner M, Hase M and Krebs W (2010) Flox Combustion at High Power Density and High Flame Temperatures. Journal of Engineering for Gas Turbines and Power. 132: 121503.

[50] Arghode VK and Gupta AK (2011) Development of High Intensity Cdc Combustor for Gas Turbine Engines. Applied Energy. 88: 963-973.

[51] Khalil AEE and Gupta AK (2011) Distributed Swirl Combustion for Gas Turbine Application. Applied Energy. 88: 4898-4907.

[52] Arghode VK and Gupta AK (2010) Effect of Flow Field for Colorless Distributed Combustion (Cdc) for Gas Turbine Combustion. Applied Energy. 87: 1631-1640.

[53] Arghode VK, Khalil AEE and Gupta AK (2012) Fuel Dilution and Liquid Fuel Operational Effects on Ultra-High Thermal Intensity Distributed Combustor. Applied Energy. 95: 132-138.

[54] Khalil AEE, Arghode VK, Gupta AK and Lee SC (2012) Low Calorific Value Fuelled Distributed Combustion with Swirl for Gas Turbine Applications. Applied Energy. 98: 69-78.

[55] Khalil AEE and Gupta AK (2011) Swirling Distributed Combustion for Clean Energy Conversion in Gas Turbine Applications. Applied Energy. 88: 3685-3693.

[56] Greenberg SJ, McDougald NK and Arellano LO (2004) Full-Scale Demonstration of Surface-Stabilized Fuel Injectors for Sub-Three Ppm Nox Emissions. ASME Conference Proceedings. 2004: 393-401.

[57] Greenberg SJ, McDougald NK, Weakley CK, Kendall RM and Arellano LO (2003) Surface-Stabilized Fuel Injectors with Sub-Three Ppm Nox Emissions for a 5.5 Mw Gas Turbine Engine. International Gas Turbine and Aeroengine Congress and Exhibition. American Society of Mechanical Engineers.

[58] Weakley CK, Greenberg SJ, Kendall RM, McDougald NK and Arellano LO (2002) Development of Surface-Stabilized Fuel Injectors with Sub-Three Ppm Nox Emissions. International Joint Power Generation Conference. American Society of Mechanical Engineers.

[59] Cabot G, Vauchelles D, Taupin B and Boukhalfa A (2004) Experimental Study of Lean Premixed Turbulent Combustion in a Scale Gas Turbine Chamber. Experimental Thermal and Fluid Science. 28: 683-690.

[60] Mcdougald NK (2005) Development and Demonstration of an Ultra Low Nox Combustor for Gas Turbines. USA DOE, Office of Energy Efficiency and Renewable Energy, Washington, D.C; Oak Ridge, Tenn.

[61] Arellano LO, Bhattacharya AK, Smith KO, Greenberg SJ and McDougald NK (2006) Development and Demonstration of Engine-Ready Surface-Stabilized Combustion System. ASME Turbo Expo 2006: Power for Land, Sea, and Air.

[62] Arellano L, Smith KO, California Energy Commission. Public Interest Energy R and Solar Turbines I (2008) Catalytic Combustor-Fired Industrial Gas Turbine Pier Final Project Report, California Energy Commission, [Sacramento, Calif.].

[63] Clark H, Sullivan JD, California Energy Commission. Public Interest Energy R, California Energy Commission. Energy Innovations Small Grant P and Alzeta C (2001) Improved Operational Turndown of an Ultra-Low Emission Gas Turbine Combustor, California Energy Commission, Sacramento, Calif.

[64] Arvind G. Rao and Yeshayahou Levy, "A New Combustion Methodology for Low Emission Gas Turbine Engines", 8th HiTACG conference, July 5-8 2010, Poznan.